Radiance of non-equilibrium Gd plasma

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Fluid, Ions and Radiation Ensemble in Integrated Plasma Modelling

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Abstract

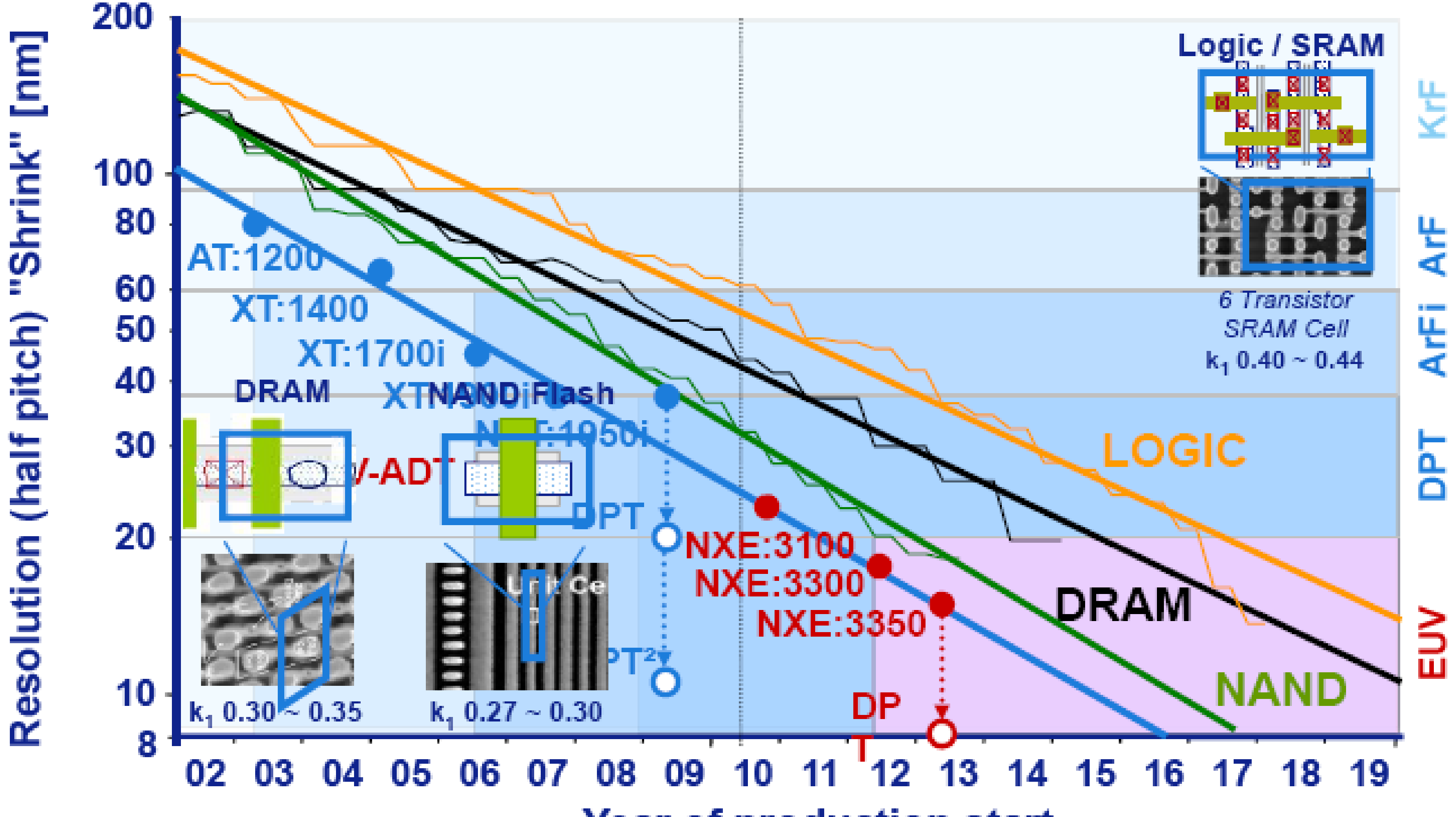
Recent results on spectral measurements for Gd and Tb plasmas show the capabilities to use these elements for the next generation of EUV and soft X-ray radiation sources. The maximum emission points located on spectrum are around 6.8 nm for gadolinium and 6.5 nm for terbium. In 0.2 nm range the necessary emission may be obtained from Gd XVII – Gd XXI ions and Tb XVIII – Tb XXII ions. These highly charged ions have a high ionization potential and for equilibrium case the temperature of plasma needs to be heated to 100 eV and higher to produce the sufficient fraction of them.

Discharge and laser produced plasmas used in soft X-ray and EUV sources are in non-equilibrium state as a rule. This leads to the mismatch between of actual conditions of the plasma and its theoretical/computational estimations, because of different effects like non-Maxwellian electron distribution, self-absorption etc. leading to change ionic compound, state populations, emission intensity and spectrum.

In the report the emission properties of non-equilibrium Gd plasma is considered and the optimal emission conditions are explored. Kinetic parameters for non-equilibrium plasma including inelastic ion interactions with non-thermal electrons, emission and absorption data are obtained in the approach based on Hartree-Fock-Slater (HFS) quantum-statistical model and distorted waves approximation.

IC & Lithography

Roadmap towards <10nm



Source: Customers, ASML, 05/10

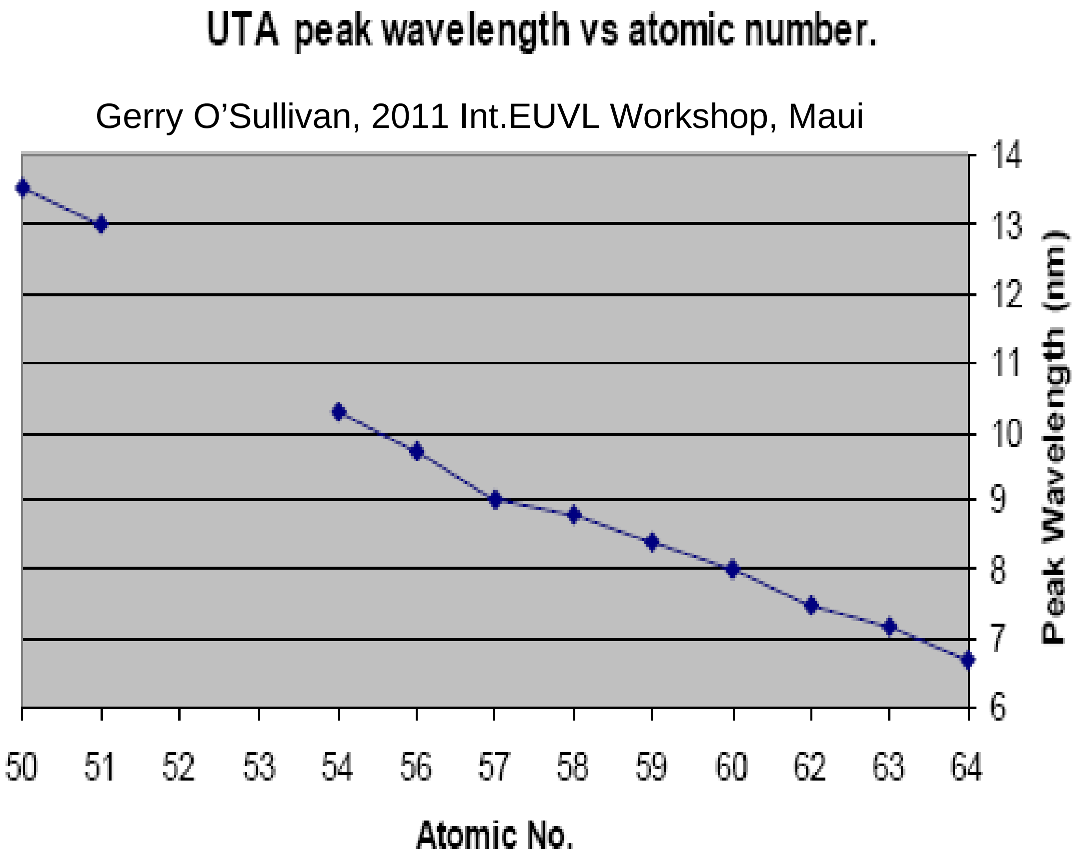
lotes:
. R&D solution required 1.5~ 2 yrs ahead of Production
. EUV resolution requires 7nm diffusion length resist
. DPT = Double Patterning

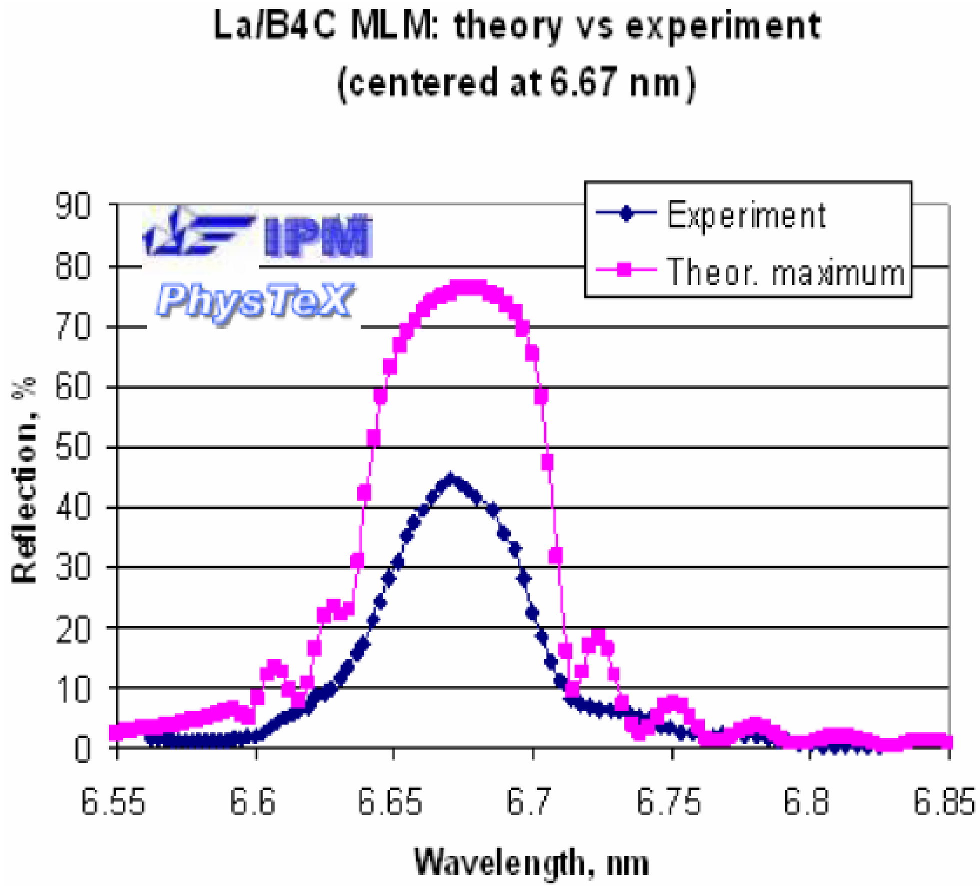
EUV source below λ=8-9 nm is interesting for future lithographic applications

ASML

6.x nm EUV source's emitter candidate

Emission and coating bands





Atomic elements from Z=50 in plasmas have strong emission in EUV wavelength region

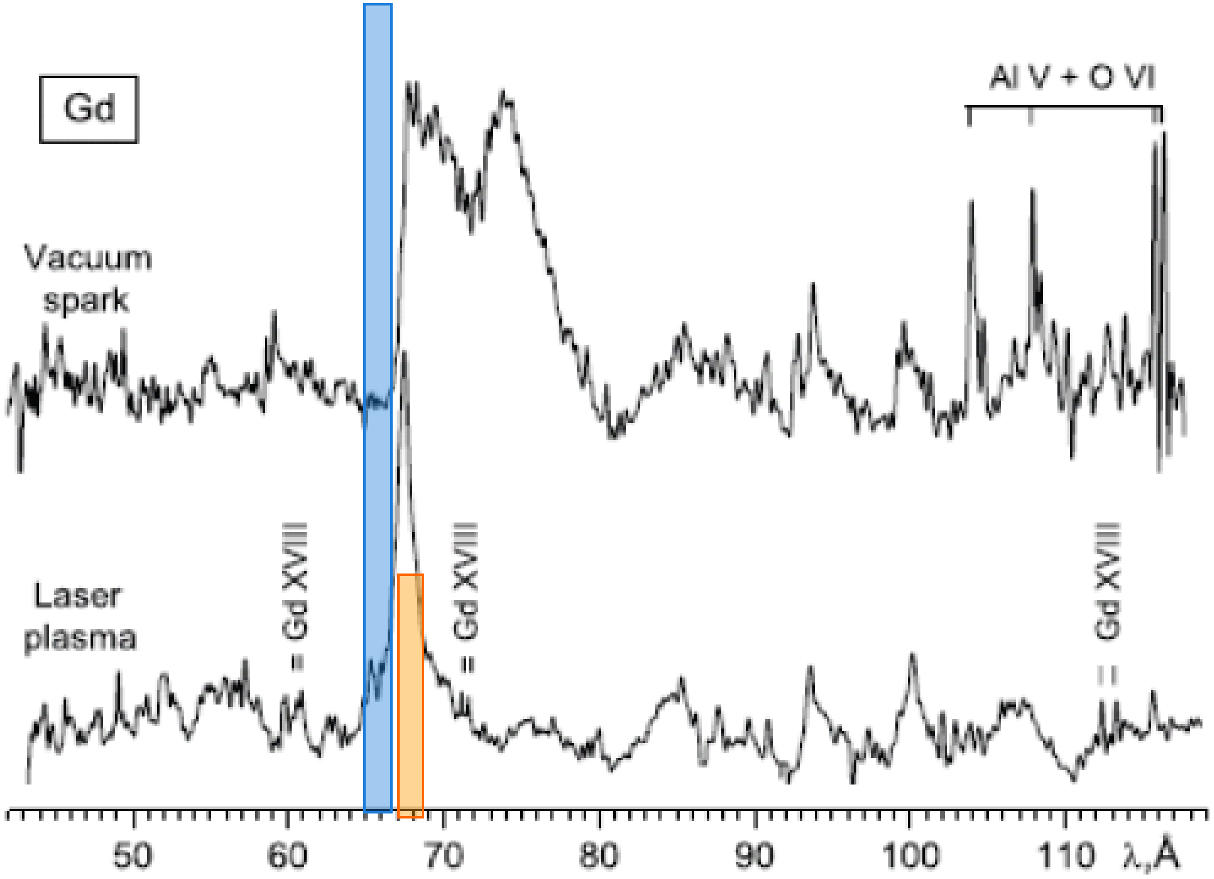
Z=64 - Gadolinium

Theoretical reflectivity <u>above 70%</u>
Experimental reflectivity <u>about 40%</u>
<u>in 0.6% bandwidth</u>

Wavelength of transition arrays

4d-4f & 4p-4d transitions

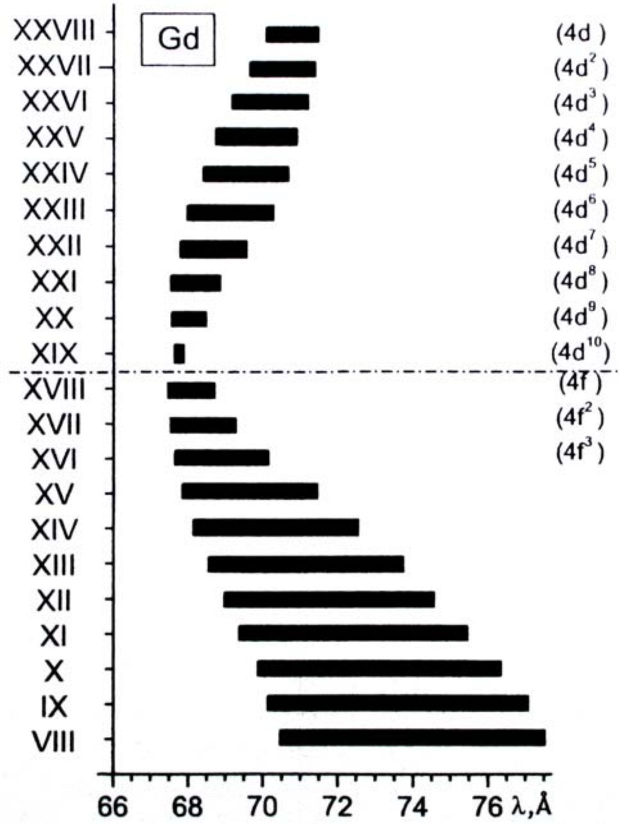
S. S. Churilov et al, Phys. Scr. 80, 045303 (2009).



Optical throughput optimized for the coating (10 mirrors)

Optical throughput optimized for the maximum emission spectrum

S. S. Churilov et al, Phys. Scr. 80, 045303 (2009)

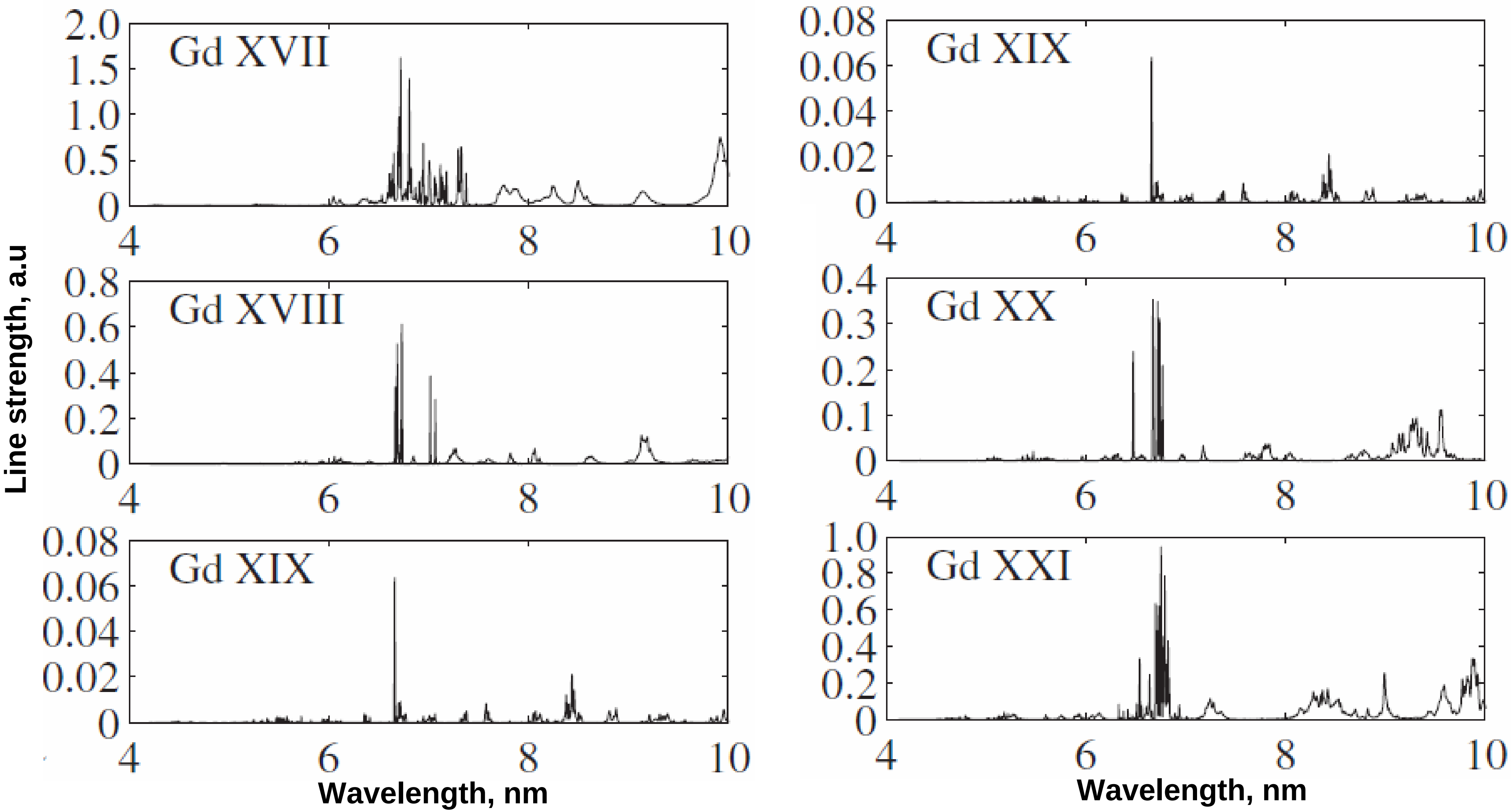


Calculated wavelength bands of the most intense 4-4 transitions in the spectra of Gd 4d- and 4f- ions

4p-4d transitions are intensive for highly ionized Gd ions only (>XXI)

Gadolinium lines

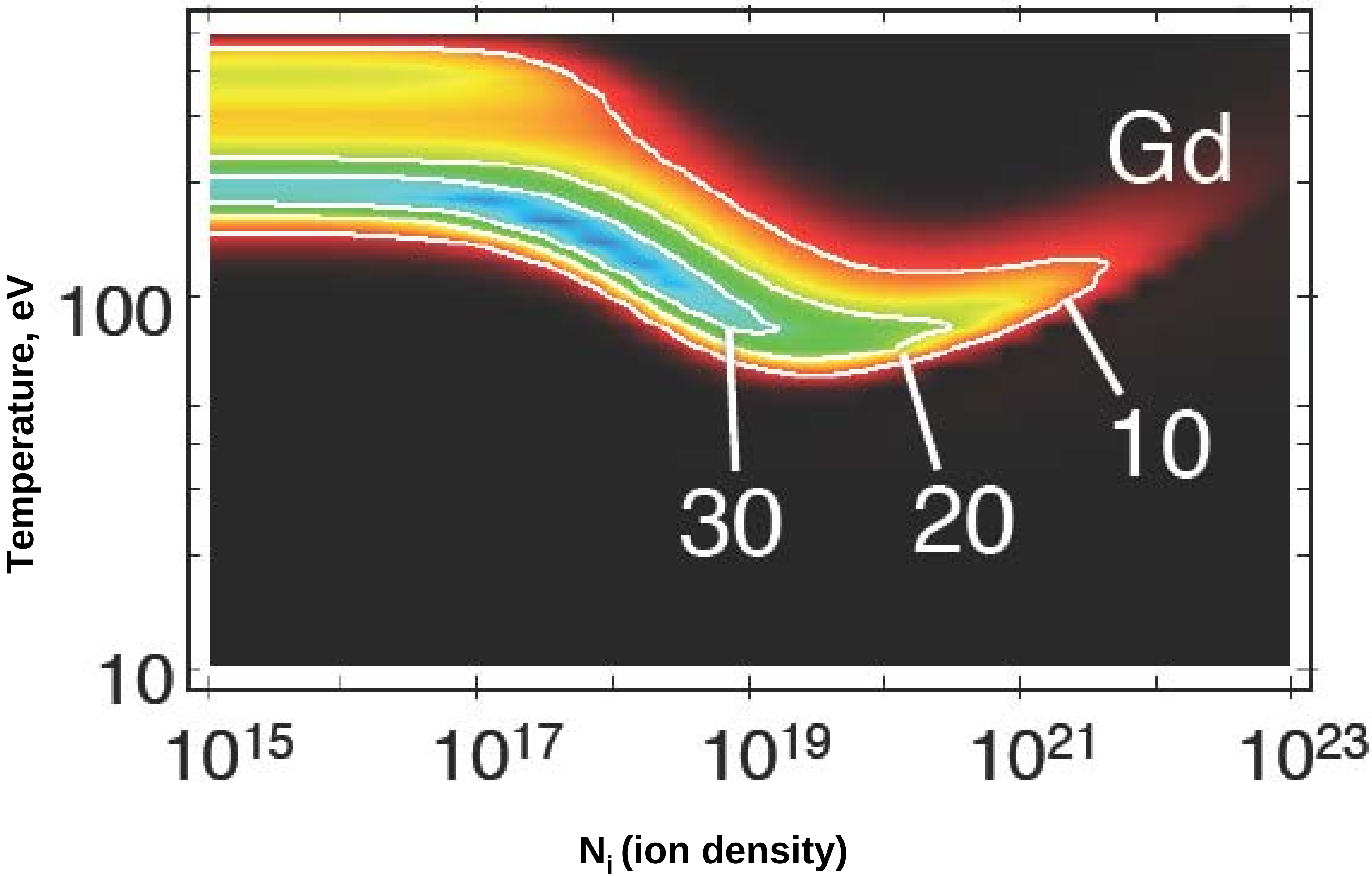
Gd XVII – Gd XXI



Line strength of Gd^{16+} - Gd^{20+} computed with FAC code including the effects of configuration interaction *[D. Kilbane and G. O'Sullivan, Jouurnal of App. Phys. 108, 104905 (2010)]*

Spectral efficiency (SE) estimated

Gd plasma in CR model



Akira Sasaki, 2011 Int.EUVL Workshop, Maui

Next Generation Modelling Tools

- knowledge transfer FP7 IAPP project FIRE

- FIRE - European FP7 Industry-Academia Partnerships and Pathways project

- The FIRE project aims to substantially redevelop the EPPRA's Z* code to include improved atomic physics models and full 3-D plasma simulation of

  ✓ plasma dynamics
  ✓ spectral radiation transport
  ✓ non-equilibrium atomic kinetics with fast electrons
  ✓ transport of fast ions/electrons
  ✓ condensation, nucleation and transport nanosize particles.

- Modelling is essential in parametric scans in EUVL source optimization, in fast particles and debris generation to solve current EUVL source problems as well as extending their application.

Radiation transfer in plasma

$$\frac{1}{c}\frac{\partial I_\omega}{\partial t}+(\vec{\Omega}\nabla)I_\omega = j_\omega - k_\omega I_\omega \quad \Rightarrow \quad \frac{\partial I_\omega}{\partial \vec{l}} = j_\omega - k_\omega I_\omega$$

- Quasi-stationary

$$U_\omega = c^{-1}\int I_\omega d\vec{\Omega};$$

- Spectral radiation energy density

$$\kappa_\omega(n_e, n_i, T_e, U_\omega);$$

- Opacity

$$j_\omega(n_e, n_i, T_e, U_\omega);$$

- Emissivity

$$I_\omega(r,z,\varphi,\theta) = \int_0^\tau \frac{j_\omega}{\kappa_\omega} e^{\tau' - \tau} d\tau;$$

- Intensity

- Cylindrical symmetry

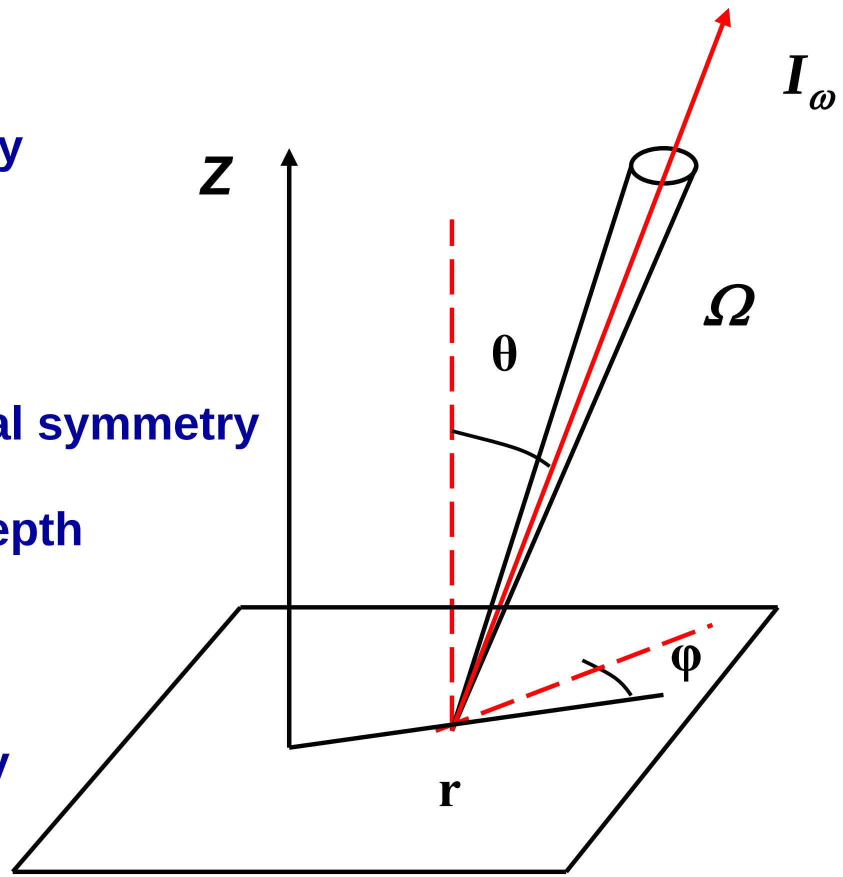
$$\tau = \tau(x) = \int_0^x \frac{\kappa_\omega(r,z)}{\sin\theta} dx;$$

- Optical depth

$$x = \sqrt{r_{out}^2 - r^2\sin^2\varphi} + r\cos\varphi$$

$$z = z_{out} + x \cdot ctg\theta$$

- Trajectory



Absorption coefficients

Bound-bound (bb), bound-free (bf) & free-free (ff) processes

$$\kappa_\omega = \kappa_\omega^{bb} + \kappa_\omega^{bf} + \kappa_\omega^{ff}$$

$$\kappa_\omega^{bb} = N_i (1 - e^{-\omega / T_e}) \sum_s P_s \sum_{\nu\mu} n_\nu^s \left(1 - n_\mu^s\right) \sigma_{\nu\mu}^{bb}$$

$$\kappa_\omega^{bf} = N_i (1 - e^{-\omega / T_e}) \sum_\nu n_\nu \left(1 - f(\varepsilon)\right) \sigma_{\nu\varepsilon}^{bf}$$

$$\kappa_\omega^{ff} = N_e (1 - e^{-\omega / T_e}) \int d\varepsilon' \, f(\varepsilon') \left(1 - f(\varepsilon)\right) \sigma_{\varepsilon\varepsilon'}^{ff}$$

$$f(\varepsilon) = 1 / \left(1 + exp((\varepsilon - \mu) / T)\right)$$

Emissivity

Emissivity (LTE): $j_\omega = \kappa_\omega I_\omega^p;$ $I_\omega^p = \dfrac{\omega^3}{e^{\omega/T}-1}$

Emissivity (general nonLTE)

$$j_\omega = j_\omega^{bb} + j_\omega^{fb} + j_\omega^{ff}$$

$$j_\omega^{bb} = N_i \omega^3 \sum_s P_s \sum_{\nu\mu} n_\mu^s \left(1 - n_\nu^s\right) \sigma_{\nu\mu}^{bb}$$

$$j_\omega^{fb} = N_i N_e \omega^3 \sum_\mu f(\varepsilon')\left(1 - n_\mu\right) \sigma_{\nu\varepsilon}^{bf}$$

$$j_\omega^{ff} = N_e N_i \omega^3 \int d\varepsilon\, f(\varepsilon)\left(1 - f(\varepsilon')\right) \sigma_{\varepsilon\varepsilon'}^{ff} \qquad \varepsilon' = \varepsilon + \omega$$

Non-Equilibrium Model

System of kinetic equations

Relative populations of levels is described by the next system of kinetic equations

$$\frac{dn_\mu}{dt} = \sum_{\nu\neq\mu}^{\nu} n_\nu \alpha_{\nu\to\mu}(N_i, N_e, T, \rho, F) -$$

$$- n_\mu \sum_{\nu\neq\mu}^{\nu} \alpha_{\mu\to\nu}(N_i, N_e, T, \rho, F), \qquad \sum_{\mu} n_\mu = 1,$$

$\boldsymbol{\alpha_{\nu\to\mu}}$ and $\boldsymbol{\alpha_{\mu\to\nu}}$ - total rates of the processes leading to increase and decrease of the level $\boldsymbol{\mu}$ population $\boldsymbol{n_\mu}$, $\boldsymbol{N_i}$ and $\boldsymbol{N_e}$ – number of ions and electrons, $\boldsymbol{T}$ – temperature, $\boldsymbol{\rho}$ – density. Total rates include a different set of processes depending of model, kind of modelling etc.

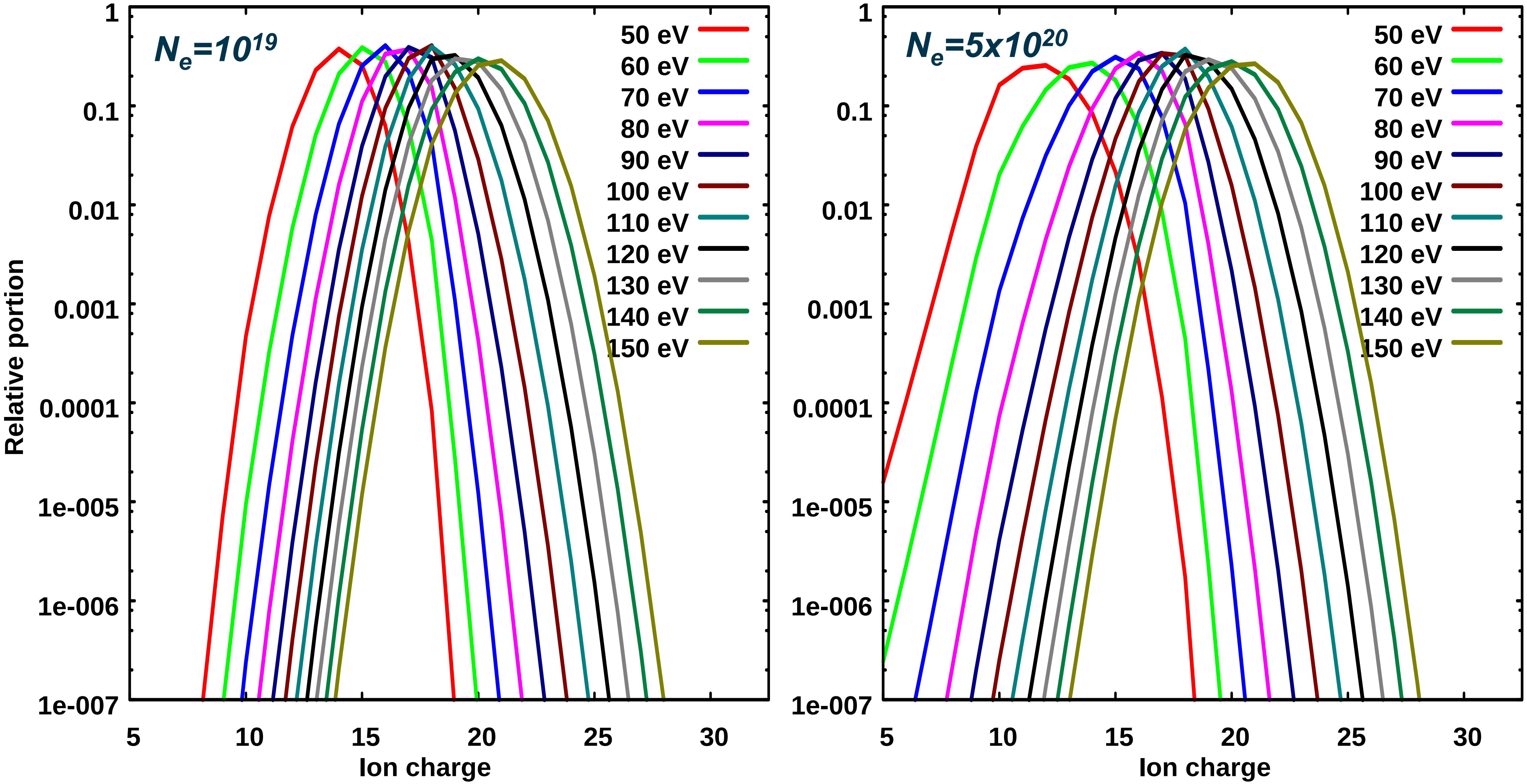
Quasi-neutrality:

$$N_e = Z_0 N_i, \qquad Z_0 = \sum_{\mu} z_\mu n_\mu,$$

$\boldsymbol{z_\mu}$ – charge of the ion of level $\boldsymbol{\mu}$, $\boldsymbol{Z_0}$ - average charge

Gadolinium plasma

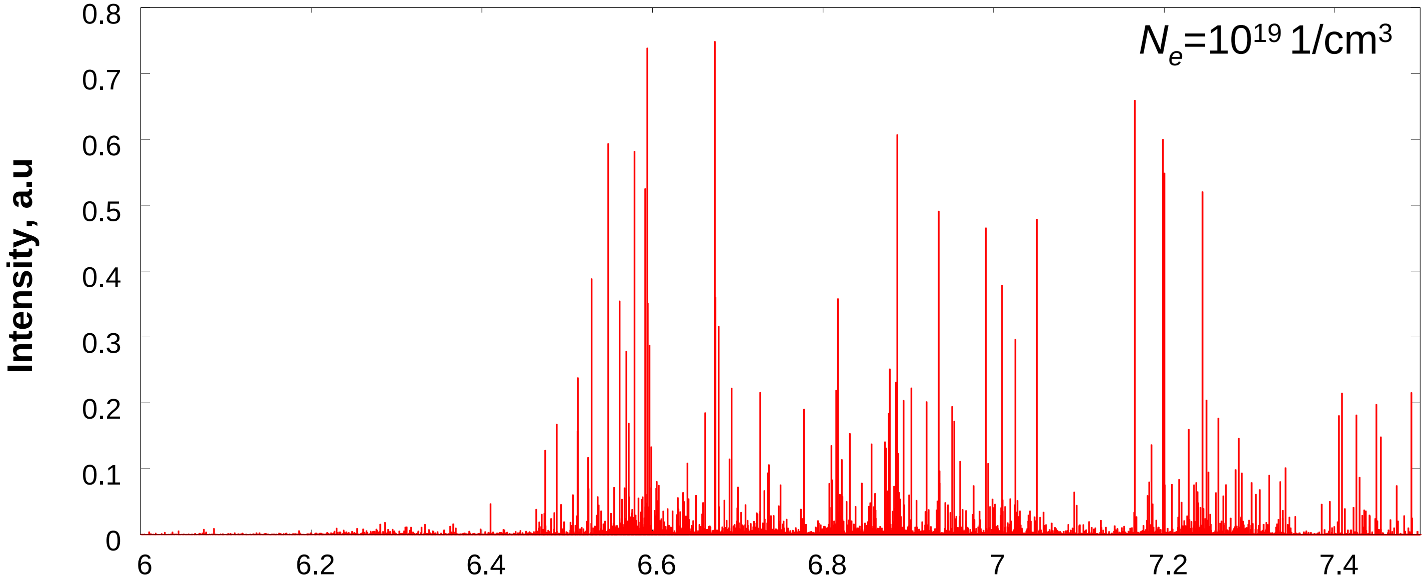
Ion populations

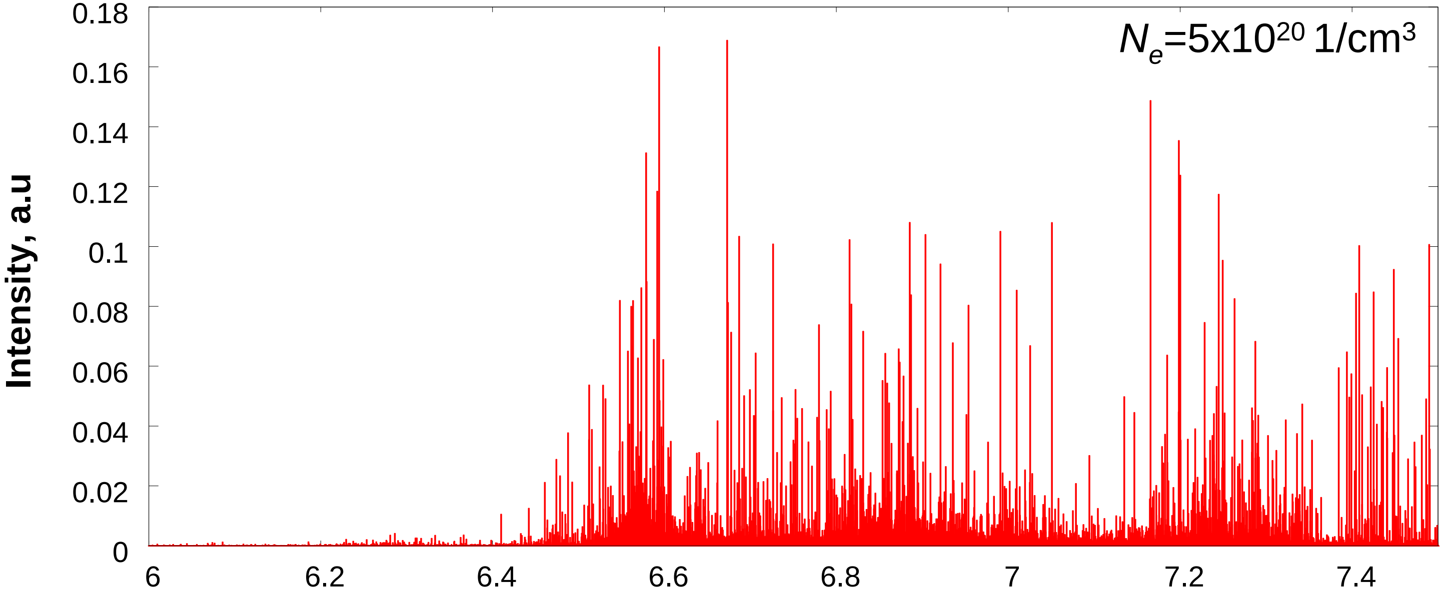


Ion distribution spreads and average charge drops as density raises →
→ for LPP very high temperature may be necessary

Gadolinium emission

Line emission spectra





T_e=60 eV

$N_e = 10^{19}$, $5\mathrm{x}10^{20}$ 1/cm^3

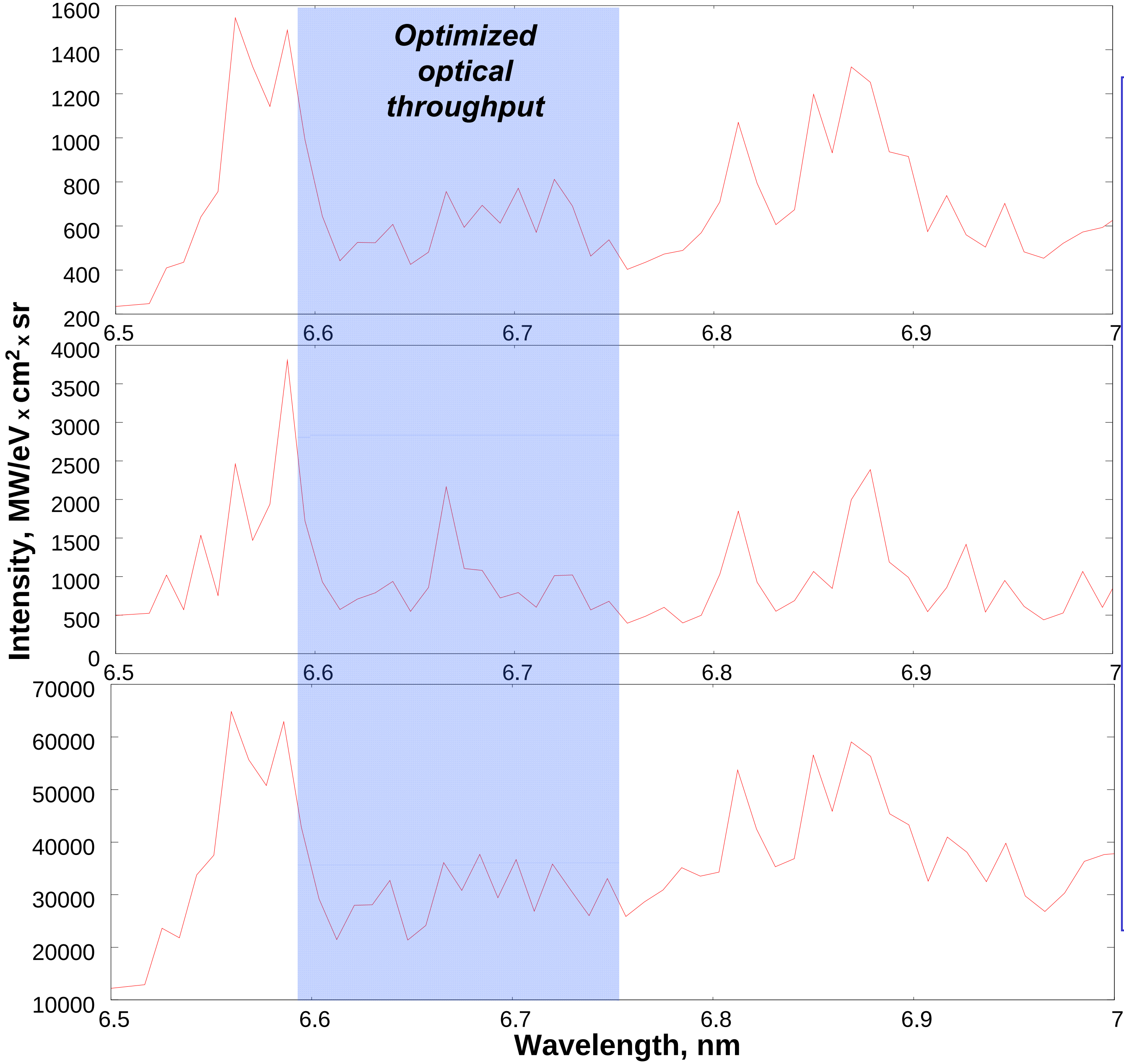
Gd^{10+} - Gd^{18+} are taken into account

Almost 1 million transitions in total

More intensive emission is from 4f-4d transitions ($4d^9 4f^m$ - $4d^{10} 4f^{m-1}$)

Efficiency in non-equilibrium Gd plasma

Spectral modeling



Detailed calculations with absorption

400 micron spherical Gd target

$N_e=10^{19}$ 1/cm^3, Te=50 eV

SE @ 6.68 nm of 0.6% bandwidth

6.3%

SE @ 6.68 nm of 2% bandwidth

17.5%

$N_e=10^{19}$ 1/cm^3, Te=60 eV

SE @ 6.68 nm of 0.6% bandwidth

5.3%

SE @ 6.68 nm of 2% bandwidth

18.5%

$N_e=5\times10^{20}$ 1/cm^3, Te=60 eV

SE @ 6.68 nm of 0.6% bandwidth

5.9%

SE @ 6.68 nm of 2% bandwidth

16.8%

Remarks

- Low charged Gd ions (XVI and below) emit well also in 6.x region
- Gd target suits for LPP applications (dense targets)
- Spectral efficiency of Gd may reach 6.3% in 0.6% waveband

The results were obtained in frame of FP7 FIRE Marie Curie action

fire

Fluid, Ions and Radiation Ensemble
in Integrated Plasma Modelling